An MEG Study of the Spatiotemporal Dynamics of Feature Binding

Filbey, F. M., Holroyd, T., Slack, K., Maltzman, L., Coppola, R., Sunderland, T., and Cohen, R. M.
National Institute of Mental Health, USA

Corresponding Author: Francesca M. Filbey, GPB, NIMH (10/4S239), 10 Center Drive, Bethesda, MD, USA 20892, Fax (301) 480-2847, Phone (301) 402-1233, Francesca.Filbey@nih.gov

ABSTRACT

Feature binding (FB) is the memory formation of a whole event from multiple parts. Previous literature, mostly from functional magnetic resonance imaging (FMRI) studies, show that FB processes elicit a neural circuit involving hippocampal, thalamic, and fronto-temporo-parietal areas. This is the first study, to our knowledge, that investigates FB using MEG. Thirteen healthy volunteers were presented with a FB task previously described [Mitchell, 2000] while a whole cortex MEG system recorded neural activities during one- and two-feature memory challenges. Synthetic aperture magnetometry analysis was used to localize sources of activities in the α, β, γ and θ bands during working memory (WM) for one feature and WM for two features. As expected, sources of activation during FB were observed in the thalamus, fusiform gyrus, parietal lobe, and dorsolateral prefrontal cortex, which support the FMRI literature. Additional significantly activated areas during FB were found in the parahippocampal gyrus, cingulate gyrus and caudate nucleus.

KEY WORDS

MEG, memory, thalamus, cingulate gyrus, dorsolateralprefrontal cortex, parietal lobe, caudate nucleus, parahippocampal gyrus

INTRODUCTION

Working memory (WM) has been widely studied in the functional magnetic resonance imaging (FMRI) literature. Of those key brain regions associated with WM functions, the dorsolateral prefrontal cortex (DLPFC; BA 8, 9, 45, 46, 47.) is thought to underlie organization, maintenance and manipulation of information [Levy, 2000], and the medial temporal cortex particularly the anterior portion of the hippocampus [Mitchell, 2000] and the posterior parietal cortex, particularly the intraparietal (IPS) to be associated with tasks requiring feature binding [Donner, 2002]. In a combined EEG-FMRI study, Kraut et al. reported γ synchronization in the thalamus, particularly in the pulvinar, during FB [Kraut, 2003]. The same was found by Ward et al. in a patient with unilateral damage to the rostral part of the pulvinar. In this case study, they reported that damage to the pulvinar led to errors in FB, in this case, of shape and color [Ward, 2002]. The aim of this study is twofold. The first goal is to characterize the dynamics of neural activity related to FB. Secondly, this study examines the use of MEG as a tool for the investigation of processes that have previously been reported in the FMRI literature, such as FB. MEG provides a finer temporal resolution than FMRI, and with current development in MEG data analysis (e.g. source mapping techniques), comparable spatial resolution.

METHODS

Continuous MEG signals sampled at a rate of 600 Hz were recorded using a 275-channel third-order gradiometer whole-cortex CTF Omega 2000 system (VSM MedTech Ltd., Coquitlam, Canada) from 13 healthy, right handed, seated controls (mean age = 26.4; 6 females) while they performed a previously described FB task [Mitchell, 2000]. Subjects participated in three separate runs of 510 s each. Each run contained sequential presentations of two of the three FB conditions. In the object (OBJ) and location (LOC) conditions, Ss were instructed to remember only the objects or the locations of the objects within a nine-square grid, respectively. In the combination condition (COMBO), Ss were asked to remember both the objects and their locations. For each 17 s trial, Ss were asked to respond to a single probe by button-pressing. Data analysis was carried out by a source mapping technique called synthetic aperture magnetometry (SAM) using CTF software. The data was parsed into control and working memory (WM) epochs. Periods prior to stimuli (6.04 seconds) were considered control epochs; WM epochs were those prior to the test cue (8.04 seconds). Changes in power between control and WM epochs were measured in the θ (3.5 – 7 Hz), α (7.5 – 13 Hz), β (14 – 30 Hz), and γ (30 – 80 Hz) bands. Following SAM analysis, the data were normalized into *z*-scores and transformed into Talairach space using Analysis of Functional NeuroImages (AFNI; Cox, RW). To look for the effect of feature binding, an analysis of variance (ANOVA) was performed to compute differences in cortical power between FB and OBJ plus LOC. Maps of statistically significant power changes were displayed on individual anatomical scans acquired using a magnetization prepared rapid gradient (MP-RAGE) sequence on a 3.0 Tesla Signa MRI scanner (124 x 1.2 mm slices, TR = 9.7 ms, TE = 4 ms; GE Medical Systems, Milwaukee, WI).

RESULTS

Changes in power appeared to be significantly greater ($F=3.16$, $p<0.05$) during the FB conditions (COMBO) compared to both non-FB conditions (OBJ, LOC) in several areas. Increased θ-band power was found in the L thalamus, L parahippocampal gyrus, and L and R anterior cingulate. De-synchronization in θ activity associated with FB was found in the L pulvinar, R inferior parietal lobe, and R posterior cingulate. In the γ-band, synchronization in the R thalamus, L fusiform gyrus, and L dorsolateral prefrontal cortex (DLPFC / BA 46), in addition to de-synchronization in the L caudate and R cingulate gyrus were found to correspond with FB. In the α-band, FB was associated with increased power in the R parahippocampal gyrus, L DLPFC (BA9), while de-synchronization was found in the R superior parietal lobe, R caudate and L posterior cingulate gyrus. β-band synchronization was found in the L DLPFC (BA 8), while de-synchronization in the R superior parietal lobe appeared to underlie FB.

Synchronization in the L DLPFC (BA 8, 9 and 46) during FB was found in the α, β and γ bands. On the other hand, consistent de-synchronization was found in the R parietal lobe in the θ, α and β bands.

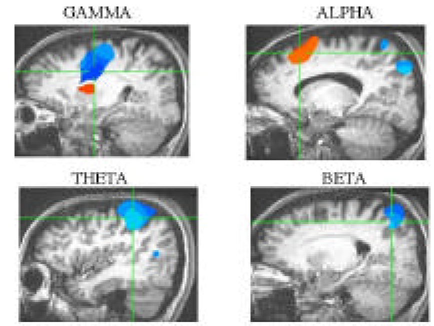

Figure 1. The largest sources per band during FB are: γ = R cingulate gyrus (27, -7, 32); α = L DLPFC (BA 6) (-16, 23, 55); θ = R inferior parietal lobe (41, -41, 51); β = R superior parietal lobe (22, -70, 46).

	θ	α	β	γ
COMBO - OBJ				
COMBO	R anterior cingulate L thalamus	L BA 6 R middle and inferior temporal lobe	L BA 9	L BA 8 R thalamus R precentral gyrus L anterior cingulate
OBJ	B/L precuneus R posterior cingulate R inferior parietal lobe	L cuneus R caudate R posterior cingulate	R superior parietal lobe	L caudate B/L cingulate gyrus
COMBO-LOC				
COMBO	L parahippocampal gyrus L anterior cingulate	L BA 6, 9, 46 R caudate	L BA 8	L BA 8, 9
LOC	R posterior cingulate B/L superior parietal lobe	R superior parietal lobe L precuneus	R superior parietal R precuneus	L caudate L lentiform nucleus R cingulate gyrus

Figure 2. Significant power increases (per condition) when COMBO was compared separately with OBJ and with LOC conditions.

DISCUSSION

These MEG findings indicate similar regions of neural activities during FB processes previously reported in the FMRI literature. In addition to those areas previously identified in fMRI studies, activity in the cingulate gyrus and caudate nucleus were also found. The cingulate gyrus has been shown to be involved in attention control and management [Luks, 2002], and response monitoring [Milham, 2002]. In a study by Postle, the caudate nucleus was reported to be a key area in spatial WM. It was postulated that the caudate is responsible for the integration of spatial information and motor response preparation [Postle, 2003]. Of interest is the synchronization across multiple frequency bands in the L DLPFC and de-synchronization in the R parietal lobe during FB. The DLPFC is well known to underlie working memory processes, particularly in the maintenance and manipulation of coded information. The parietal area has also been linked to FB processes. It is posited that the parietal lobe plays a role in the efficiency of attention [Nobre, 2003]. Thus, it is not surprising that both of these regions were robustly activated in several of the frequency bands. Although we did not find a significant difference in hippocampal activation as expected, an increase in power in the parahippocampal gyrus in the α and θ bands was found. It is possible that the lack of hippocampal activation may indicate that there is no difference in the maintenance of one feature versus two features, but that there is a difference in the recognition of the information between the two conditions [Ranganath, 2001]. It is also possible that the MEG technique might not be sensitive to the type of activation that is detected in the FMRI studies. The greatest activity in terms of size and number was found in the γ and θ bands. γ-band activity during attention and memory have often been reported in both EEG and MEG literature [Kraut, 2003]. In a meta-analysis by Bastiaansen, θ-band oscillations were postulated to be involved in cell assembly formations that lead to WM [Bastiaansen, 2003]. These results are for a fairly wide time window (i.e., 6 - 8 s); therefore, further analyses are planned to utilize the temporal resolution of MEG. In conclusion, this study gives evidence for the usefulness of MEG in investigating WM processes in terms of FB.

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